

Pressure effects on the superconducting thin film $\text{Ba}_{1-x}\text{K}_x\text{Fe}_2\text{As}_2$

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We report electrical resistivity measurements on a high-quality $\text{Ba}_{1-x}\text{K}_x\text{Fe}_2\text{As}_2$ thin film ($x = 0.4$) under pressure. The superconducting transition temperature ($=39.95$ K) of the optimally-doped thin film shows a dome shape with pressure, reaching a maximal value 40.8 K at 11.8 kbar. The unusually high superconducting transition temperature and its anomalous pressure dependence are ascribed to a lattice mismatch between the LaAlO_3 substrate and the thin film. The local temperature exponent of the resistivity ($n = d\ln\Delta\rho/d\ln T$) shows a funnel shape around the optimal pressure, suggesting that fluctuations associated with the anomalous normal state are responsible for high-temperature superconductivity.

Since the report of superconductivity in F-doped $\text{LaFeAsO}_{1-x}\text{F}_x$ [1], Fe-based superconductors have attracted strong interest because of their high superconducting transition temperature (high- T_c) and the size of the materials space where superconductivity is discovered [2]. Similarity to the cuprate superconductors has been pointed out in that superconductivity is introduced when carriers are induced by hole/electron doping the antiferromagnetic parent compounds and FeAs or FeSe layers are deeply involved in the superconductivity as the CuO layers are in the high- T_c cuprates. It has been recently suggested that the anion height measured from the Fe plane is an important parameter that controls the Fermi surface topology and consequentially the superconductivity [3, 4]. There exists an optimal height (h_m) where the superconducting transition temperature is a maximum and T_c decreases as the height departs from h_m .

Thin films grown on different types of single crystal substrates may manifest uniaxial pressure effects because a lattice mismatch relative to the substrate leads to either contraction or expansion of the film and a change in the anion height [5]. Iida *et al.* reported that T_c of a $\text{Ba}(\text{Fe},\text{Co})_2\text{As}_2$ (Co-Ba122) thin film changes from 16.2 to 24.5 K with increasing c/a , where the out-of-plane lattice parameter c decreases with an increase of the in-plane lattice constant a for different types of substrates [6]. Bellingeri *et al.* found that the T_c of 21 K for a $\text{FeSe}_{0.5}\text{Te}_{0.5}$ thin film is significantly higher than 16.2 K for a bulk crystal, suggesting that strain effects in thin films may provide a way to raise T_c [7].

Despite the ever growing interest in thin film studies, however, the high volatility of the doping elements often makes it difficult to fabricate thin films of the iron-pnictide superconductors. An electron-doped $\text{BaFe}_{2-x}\text{Co}_x\text{As}_2$ thin film with $T_c \approx 20$ K has been synthesized with relative ease because cobalt atoms have a lower vapor pressure, while a hole-doped $\text{Ba}_{1-x}\text{K}_x\text{Fe}_2\text{As}_2$ thin film has been fabricated only recently by overcoming the technical difficulty of a large difference in the

vapor pressures of constituent elements [8–13]. Lee *et al.* recently reported successful synthesis of a thin film of $\text{Ba}_{0.6}\text{K}_{0.4}\text{Fe}_2\text{As}_2$, where T_c is as high as 40 K [12]. Here we report for the first time the dependence of superconducting properties on externally applied pressure for a $\text{Ba}_{0.6}\text{K}_{0.4}\text{Fe}_2\text{As}_2$ thin film. Unlike single crystalline compounds, T_c of the optimally doped thin film does not decrease monotonically with pressure but rather shows a dome centered around 11.8 kbar ($=P_c$). The electrical resistivity of the film in the normal state shows an anomalous power-law temperature dependence under pressure. The local temperature exponent of the resistivity shows a funnel shape above the optimal pressure P_c , suggesting that fluctuations relevant to anomalous normal state properties are responsible for high- T_c superconductivity in the Fe-pnictides superconductors.

Optimally doped thin films of $\text{Ba}_{0.6}\text{K}_{0.4}\text{Fe}_2\text{As}_2$ were grown on LaAlO_3 (001) substrates by a pulsed laser deposition (PLD) method, and X-ray diffraction measurements showed that films with a tetragonal structure grow preferentially along the crystalline c -axis [12]. The lattice parameters determined from a least-squares refinement of the x-ray pattern are $a = 3.9068$ Å and $c = 13.4037$ Å, where $c/a = 3.4308$ is slightly larger than that of optimally doped bulk crystals ($=3.40$) [14]. Electrical resistivity of the K-doped BaFe_2As_2 thin film was measured by a standard four-probe technique in a closed cycle refrigerator (CCR). A clamp-type Be/Cu hybrid cell with a NiCrAl alloy insert was used for resistivity measurements up to 28.2 kbar, and a change in the resistivity of an annealed manganin wire was used as a pressure monitor at room temperature [15].

Figure 1 shows the temperature dependence of the in-plane electrical resistivity ρ of a thin film of $\text{Ba}_{0.6}\text{K}_{0.4}\text{Fe}_2\text{As}_2$ under pressure. As shown in the inset, the onset temperature of a superconducting (SC) phase transition (T_c^{onset}), which is defined as the deviation point from a linear temperature dependence of the resistivity in the normal state (dotted line), is 39.95 K at ambient pressure, the highest for optimally doped films on a LaAlO_3 (LAO) substrate. The SC transition width, the difference between a 10 % to 90 % drop of the normal state resistivity at T_c^{onset} , is 1.30 K and the residual resistivity ratio (RRR) $\rho(300\text{ K})/\rho(0\text{ K})$ at 1 bar is

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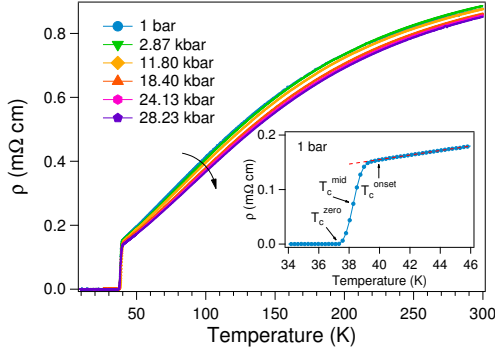


FIG. 1: (color online) Electrical resistivity of a $\text{Ba}_{0.6}\text{K}_{0.4}\text{Fe}_2\text{As}_2$ thin film deposited on a LaAlO_3 (LAO) substrate under pressure. The arrow indicates a pressure increase from 1 bar to 28.23 kbar. Inset: The resistivity at ambient pressure is displayed near SC transition temperature.

38, indicating the high quality of this thin film. Here, $\rho(0 \text{ K}) = 0.023 \text{ m}\Omega\text{cm}$ is an extrapolated value from the $\rho = \rho(0 \text{ K}) + AT^{1.2}$ dependence in the normal state. Externally applied pressure monotonically reduces the resistivity in the normal state because of an increased overlap among adjacent ligand orbitals under pressure: ρ at 41 K and 300 K decreases at a rate of -0.6 and $-1.1 \times 10^{-3} \text{ m}\Omega\text{cm/kbar}$, respectively.

The pressure evolution of superconducting transition temperatures is plotted in Fig. 2, where T_c^{onset} , T_c^{mid} , and T_c^{zero} represents the onset, midpoint and zero-resistance transition temperatures, respectively (see the inset of Fig. 1). T_c^{onset} gradually increases from 39.95 K at 1 bar to 40.8 K at 11.80 kbar and then decreases with further increasing pressure, showing a dome-shaped superconducting phase centered on the optimal pressure $P_c (=11.80 \text{ kbar})$. Such pressure effects on the thin film are unexpected because T_c of single crystals with similar stoichiometry is continuously suppressed with pressure [16, 17]. For $\text{Ba}_{1-x}\text{K}_x\text{Fe}_2\text{As}_2$ bulk crystals, the c/a ratio almost linearly increases with potassium concentration x and is approximately 3.410 for an optimally K-doped compound ($x = 0.4$) [14]. The ratio $c/a = 3.4308$ observed in our thin film corresponds to an overdoped concentration $x = 0.46$ for a bulk crystal, ruling out the possibility that the thin film on LAO is underdoped. In addition, the T_c of 39.95 K is too high for any underdoped compound. For comparison, T_c of an optimally doped bulk crystal is 38 K [14, 18].

The unusual pressure dependence of the optimally doped thin film may be ascribed to a high c/a ratio that arises from a lattice mismatch between the film and LAO substrate. It has been reported that the c/a ratio of a $\text{Ba}_{0.6}\text{K}_{0.4}\text{Fe}_2\text{As}_2$ thin film deposited on Al_2O_3 (AO) and LaAlO_3 (LAO) substrates is 3.4028 and 3.4308, respectively [12]. The superconducting transition temperature of a film on a AO substrate is almost 1 K higher than that on a LAO substrate, indicating that the anion height of a

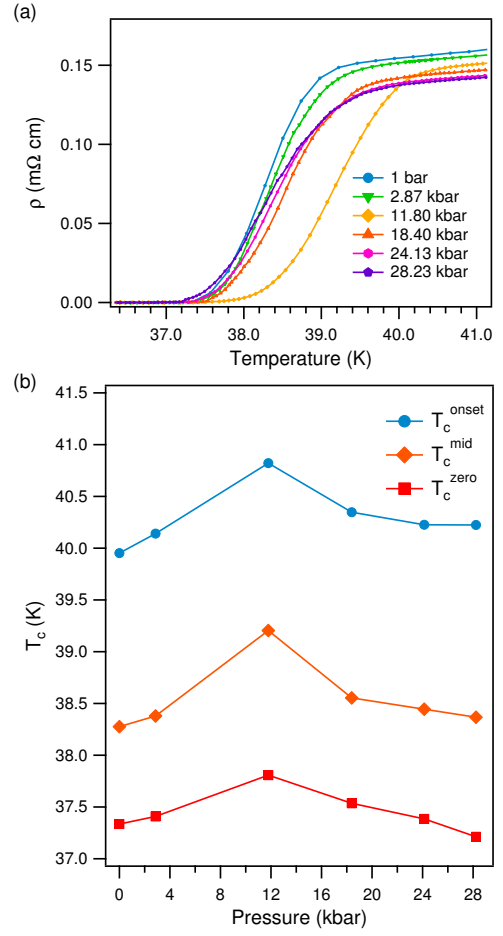


FIG. 2: (color online). (a) Pressure dependence of the resistivity of a $\text{Ba}_{1-x}\text{K}_x\text{Fe}_2\text{As}_2$ ($x = 0.4$) thin film near its superconducting transition temperature. (b) Superconducting transition temperature vs pressure phase diagram, where T_c^{onset} , T_c^{mid} , and T_c^{zero} represent the onset, midpoint, and $\rho = 0$ SC transition temperatures, respectively.

AO-film is close to the optimal height h_m , while the anion height of a film on LAO is slightly larger than h_m . Lattice constants of the LAO substrate are almost independent of hydrostatic pressure and isotropic among crystalline axes: the relative change in lattice constants being only 0.55% at 32.1 kbar [19]. In contrast, the lattice constants of a tetragonal BaFe_2As_2 single crystal are compressed significantly both along the crystalline a - and c -axes with pressure: at 32.1 kbar, the lattice constant a and c decreases by 1.03 and 2.02%, respectively [20]. When the thin film of $\text{Ba}_{0.6}\text{K}_{0.4}\text{Fe}_2\text{As}_2$ is under hydrostatic pressure, it effectively experiences a uniaxial pressure along the c -axis because the change in the lattice constant a is almost negligible because it is pinned to the substrate lattice, while the lattice constant along the c -axis is compressed as easily as in a single crystal. Consequently, hydrostatic pressure acts as an effective uniaxial pressure along the c -axis and controls the anion height of the film to the optimal h_m at 11.8 kbar, therefore making

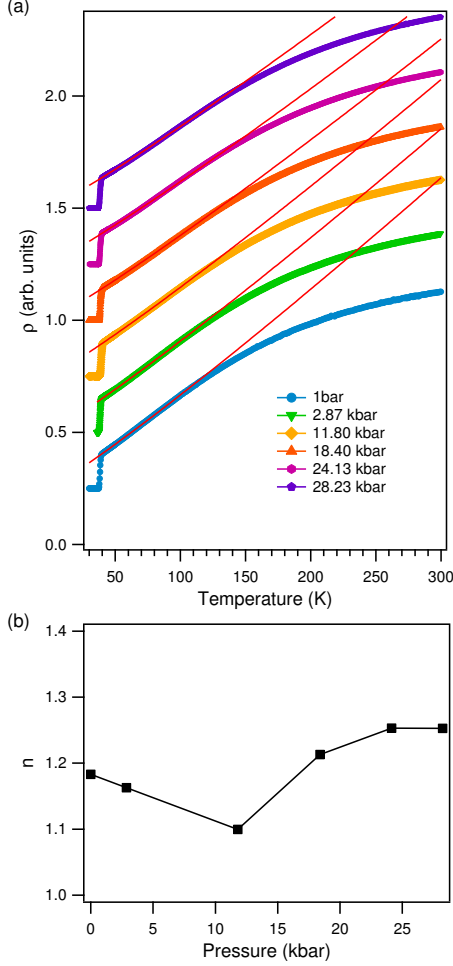


FIG. 3: (color online). (a) Temperature dependence of the resistivity of $\text{Ba}_{1-x}\text{K}_x\text{Fe}_2\text{As}_2$ ($x = 0.4$) under pressure and a least-squares fit of $\rho = \rho_0 + AT^n$ (solid lines). The resistivity under pressure is shifted rigidly upwards for clarity. (b) Pressure dependence of the resistivity coefficient n of the power-law form.

the dome-shaped SC phase under pressure.

Figure 3(a) displays the temperature dependence of the resistivity of the $\text{Ba}_{0.6}\text{K}_{0.4}\text{Fe}_2\text{As}_2$ thin film on the LAO substrate for several pressures. Regardless of the applied pressure, a power-law form of $\rho = \rho_0 + AT^n$ best describes the normal state resistivity over an extended temperature range above T_c , where the exponent n of the resistivity changes between 1.1 and 1.25 under pressure (see Fig. 3(b)). The anomalous temperature exponent n is consistent with previous work on single crystals that reported a gradual change of n from 2 (undoped) to 1 (at optimal potassium doping) [21].

Figure 4 plots the local temperature exponent of the resistivity ($n = d\ln\Delta\rho/d\ln T$) in T - P phase space, where $\Delta\rho = \rho(T) - \rho(T = 0\text{ K})$. The local exponent n is less than 1.25 below 100 K in the measured pressure range, which is comparable to the results via a global

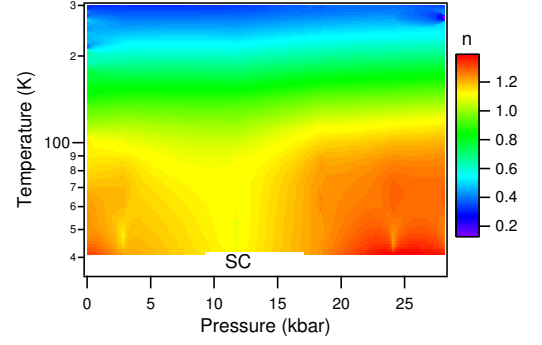


FIG. 4: (color online). Evolution of the local temperature exponent n of a $\text{Ba}_{0.6}\text{K}_{0.4}\text{Fe}_2\text{As}_2$ thin film is plotted in the temperature-pressure phase space. The local exponent is defined as $n = d\ln\Delta\rho/d\ln T$, where $\Delta\rho = \rho(T) - \rho(T = 0\text{ K})$.

fit of the resistivity (see Fig. 3(a)). The local analysis, however, reveals a delicate topology in the resistivity exponent, showing a funnel shape with $n = 1.1$ above the optimal pressure. Even though the optimally doped $\text{Ba}_{0.6}\text{K}_{0.4}\text{Fe}_2\text{As}_2$ thin film at 1 bar is probably in the vicinity of a quantum critical point (QCP), external pressure sensitively tunes the film right to the QCP where the associated quantum fluctuations diverge. A similar analysis based on the local resistivity exponent has been performed to show evidence for quantum critical behavior in other iron-pnictides superconductors as a function of chemical doping [22], which inherently incur disorder whose effects on the electron scattering may change with doping concentration. In this work, the K-doped Ba122 thin film with $x = 0.4$ was sensitively tuned to a critical point via pressure, thus allowing us to study the quantum critical behavior without incurring additional disorder. A funnel shaped resistivity exponent above an optimal pressure has been also reported in the pressure-induced heavy fermion superconductor CeRhIn_5 [23]. Future characterization of the spectra of quantum fluctuations that are pertinent to the high SC transition temperature in iron-pnictides superconductors requires simultaneous tuning of such external parameters as pressure, magnetic field, and low temperatures.

We fabricated $\text{Ba}_{1-x}\text{K}_x\text{Fe}_2\text{As}_2$ ($x = 0.4$) thin films on a LaAlO_3 substrate, where T_c is 39.95 K. The sharp superconducting phase transition ($\Delta T_c = 1.30\text{ K}$) and large residual resistivity ratio (RRR = 38) indicate high quality of the film. Unlike single crystals with similar stoichiometry, T_c of the thin film with optimal potassium concentration gradually increases to 40.8 K at 11.8 kbar (P_c) and decreases with further increasing pressure, showing a dome shape. The unusual pressure dependence of T_c is ascribed to a lattice mismatch between the LAO substrate and thin film, where applied hydrostatic pressure effectively acts as uniaxial pressure along the crystalline c -axis of the film. The local temperature exponent of the resistivity reveals a funnel-shaped

topology surrounding the optimal pressure P_c , indicating the presence of a quantum critical point where the normal-state properties are dominated by the associated quantum fluctuations.

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